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On radiations from a conically depressed microstrip antenna in plasma

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Abstract : A conically depressed conducting microstrip structure can be constructed to radiate electromagnetic energy in space. The radiation properties of such antenna in an ionized plasma medium are studied theoretically using hydrodynamic equations and potential function technique. The total radiated power, radiation conductance, radiation efficiency and the bandwidth are calculated for different values of plasma to source frequency (ω_p/ω) It is observed that the radiated power, the efficiency and the bandwidth are changed considerably by changing the half-cone angle as well as a plasma to source frequency (ω_p/ω) values.

Keywords : Field patterns, radiation conductance, efficiency and bandwidth.

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1. Introduction

Printed circuit antennas have been applied to a variety of systems such as high-flying aeroplanes and satellites [1] due to their light weight, low cost and easy fabrication technique. However its low bandwidth becomes a disadvantage and hence reduces its application for different purposes. Constant efforts are being made to improve the bandwidth of such radiators.

One way to improve the bandwidth is that the patch surface of a circular microstrip antenna is depressed slightly into the substrate material which gives the structure of a conically depressed microstrip antenna [2]. Another way is, by increasing the substrate thickness between the ground plane and the conducting patch [3]. Radiation properties of a conically depressed radiator are investigated in warm ionized plasma medium in this communication. Radiation properties of a circular patch microstrip antenna are already studied in plasma medium using cavity model and results are presented elsewhere [4].

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Due to the conical depression of circular patch surface into the substrate by an angle ψ, an additional electric field in the radial direction will be introduced which will give rise to extra radiations. Using this additional field in addition to the already existing fields, radiation properties of a conically depressed microstrip patch antenna are studied in warm ionized plasma medium.

2. Theoretical analysis and radiating element

Geometry and coordinate system of a dimensionally thin conically depressed microstrip patch antenna is shown in Figure 1.

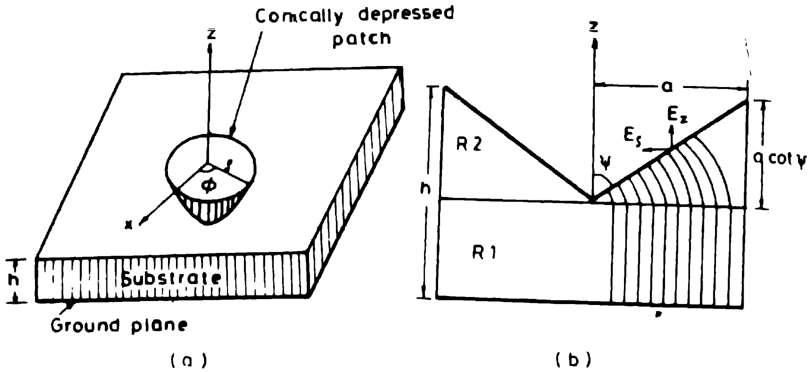

Figure 1(a). A conically depressed microstrip patch antenna with its coordinate system.

Figure 1(b). Vertically cut cross-section of a conically depressed microstrip patch antenna.

A circular patch ($\psi = 90°$) of radius "a" in x–y plane is depressed conically ($\psi = \psi°$) along the z-axis. Thickness of the substrate is considered to be "h", relative permittivity and permeability are $\varepsilon_r > 1$ and $\mu_r = 1$ respectively. Basic assumptions and initial equations regarding a plasma medium are given elsewhere [5].

The internal fields in region R1 of such a radiator, excited in TM mode are :

$$E_z = E_0 J_n(K\rho)\cos n\phi,$$

$$H_\rho = \left(-j\omega\varepsilon n/K^2\rho\right)E_0 J_n(K\rho)\sin n\phi,$$

$$H_\phi = \left(-j\omega\varepsilon/K\right)E_0 J_n'(K\rho)\sin n\phi,$$

where n is an integer, $K = \omega(\mu_0\varepsilon_0\varepsilon_r)$, ε_0 is the free space permittivity, ε_r is the relative permittivity of substrate.

$\varepsilon = \varepsilon_r\varepsilon_0$, $J_n(K\rho)$ is the Bessel function of order n and $J_n'(K\rho)$ is the derivative of the Bessel function with respect to its argument.

Due to depression of a conducting circular patch into the dielectric substrate by an angle ψ, the internal fields will be modified. In region R2, a radial field E_ρ will get excited

The magnitude of E_ρ is zero at $z = 0$ and equal to $E_z \cot \psi$ at $z = \rho \cot \psi$ (as a boundary condition) with uniform variation along the z-direction.

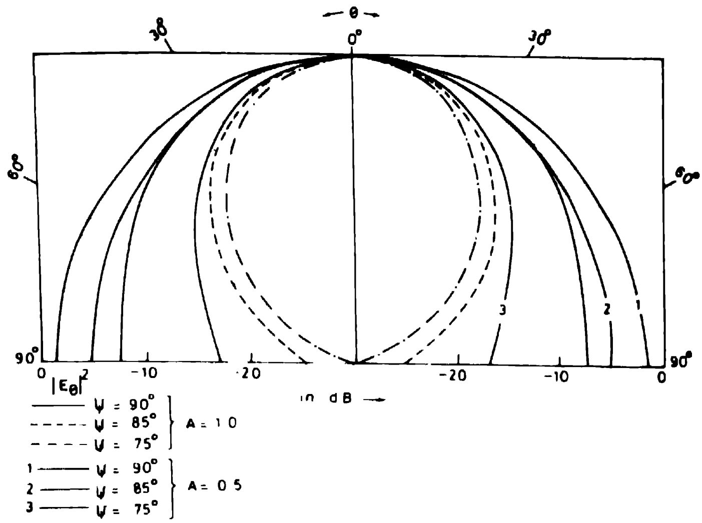

Figure 2. $|E_\theta|$ component of antenna for $A = 1.0$ and $A = 0.5$ and for different half cone angles.

Excitation of E_ρ in region R2 will create H_z and E_ϕ in addition to the field components already existing in region R1.

In region R2, the E_z and E_ρ components are related as :

$$E_z = (-\rho/z)E_\rho$$

and E_ρ at resonance will be given by

$$E_\rho = \left(-j\omega\mu_0/K^2\rho\right)\left(\partial H_z/\partial\phi\right)$$

where, $$H_z = \left(-j\omega\varepsilon\rho/n\right)\cot\psi E_0 J_n(K\rho)\sin n\phi$$

Following the method of [5], the far zone components of electromagnetic mode and plasma mode are computed. These are :

(i) For electromagnetic mode :

$$|E_\theta| = \left[\left(\beta_e a/r\right)V_0\cos\phi J_1'\left(\beta_e a\sin\theta\right) + \left(\beta_e a^2/rh\right)V_0\cot\psi\cos\phi J_1'\left(\beta_e a\sin\theta\right)\right]$$

$$|E_\phi| = \left[\left(\beta_e a/r\right)V_0\cos\theta\sin\phi\left(J_1(\beta_e a\sin\theta)/\beta_e a\sin\theta\right) + \left(\beta_e a^2/rh\right)V_0\cot\psi\cos\theta\sin\phi\left(J_1(\beta_e a\sin\theta)/\beta_e a\sin\theta\right)\right]$$

(ii) For plasma mode :

$$\left|E_p\right| = \left[60\pi(1-A^2)/rA^2\right](c/v_0)V_0\sin\phi J_1(\beta_p a\sin\theta)$$

$$\left[\sin(\beta_p h/2\cos\theta)/(\beta_p h/2\cos\theta)\right] \times \left[1 + (a^2/h)\cot\psi\right]$$

here, edge voltage at $\phi = 0$ is $V_0 = hE_0J_n(k\rho)$

with $\beta_p = [(c/v_0)\beta_e A]$ and $\beta_e = (2\pi/\lambda_0)A$ are the propagation constant in plasma mode and electromagnetic respectively.

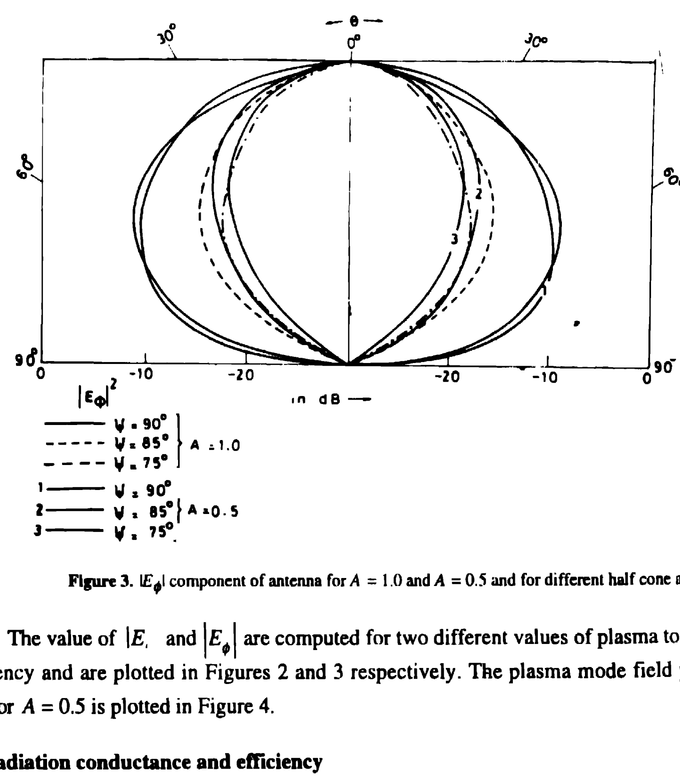

Figure 3. $|E_\phi|$ component of antenna for $A = 1.0$ and $A = 0.5$ and for different half cone angles

The value of $|E_\theta|$ and $\left|E_\phi\right|$ are computed for two different values of plasma to source frequency and are plotted in Figures 2 and 3 respectively. The plasma mode field pattern $\left|E_p\right|$ for $A = 0.5$ is plotted in Figure 4.

3. Radiation conductance and efficiency

The radiation conductance is obtained by integrating the complex Poynting vector over the upper-half space. Hence the radiation conductance in :

(i) Electromagnetic mode :

$$G_e = \left[G_e\right]_{\text{Due to R1 region}} + \left[G_e\right]_{\text{Due to R2 region}}$$

$$G_e = (A/2)\pi\sqrt{\varepsilon/\mu_0}\left[\beta_e^2a^2I_1 + I_2\right]\left[1 + (4\varepsilon_{\text{eff}}/A^2)(a\cot\psi)^2(a^2/h^4\right]$$

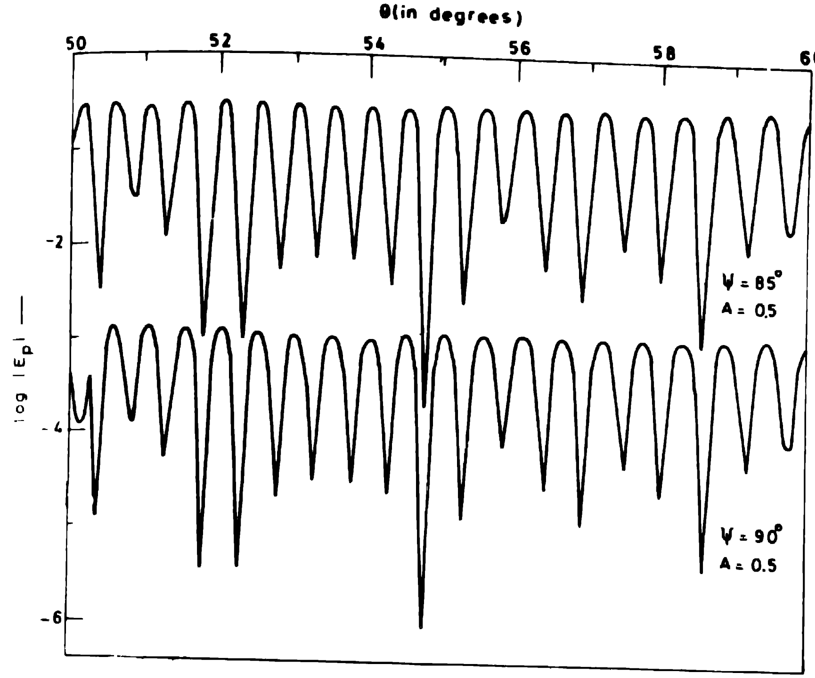

Figure 4. $|E_p|$ component of antenna for $A = 0.5$ and for different half cone angles.

(ii) *Plasma mode :*

$$G_p = \left[G_p\right]_{\text{Due to R1 region}} + \left[G_p\right]_{\text{Due to R2 region}}$$

$$\left|G_p\right| = \left[60\pi^2(1-A^2)/A\right](c/v_0)\left[I_3\right]\left[1 + (a^2/h^4)(a\cot\psi)^2\right]$$

where,
$$I_1 = \int_0^{\pi} J_1'^2(\beta_e a\sin\theta)\sin\theta\, d\theta$$

$$I_2 = \int_0^{\pi} J_1^2(\beta_e a\sin\theta)(\cos^2\theta/\sin\theta)\, d\theta$$

$$I_3 = \int_0^{\pi}\left[\left(\sin(\beta_p h/2\cos\theta)/(\beta_p h/2\cos\theta)\right)J_1(\beta_p a\sin\theta)\right]^2\sin\theta\, d\theta$$

On substituting $\psi = 90°$, all expressions derived here, readily reduces to those of a circular patch microstrip antenna in plasma medium [4]. The values of G_e and G_p are calculated and plotted for different half cone angle values ψ and a plasma parameter (A) in Figure 5.

The radiation efficiency η is defined as :

$$\eta = \left[P_e/(P_e + P_p)\right] \times 100\,\%$$

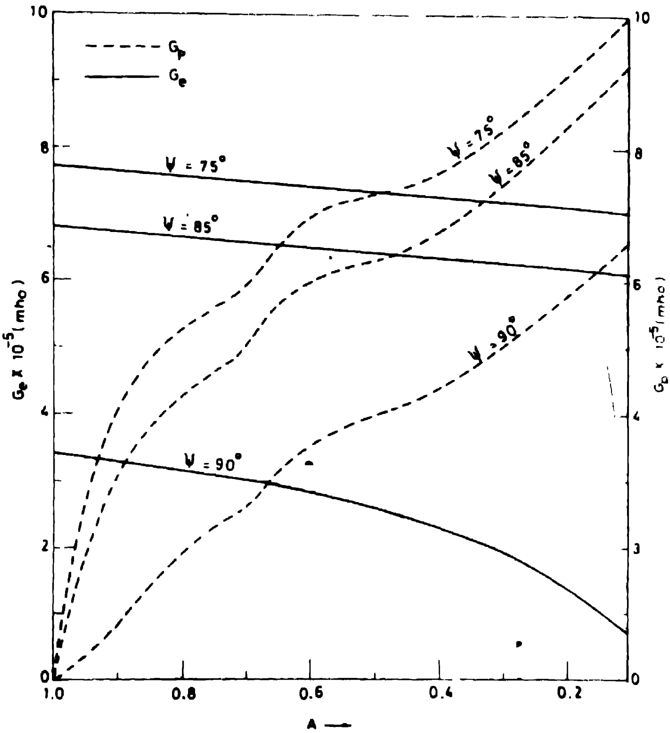

Figure 5. Variation of radiation conductances G_e and G_p with plasma parameter for different half cone angles.

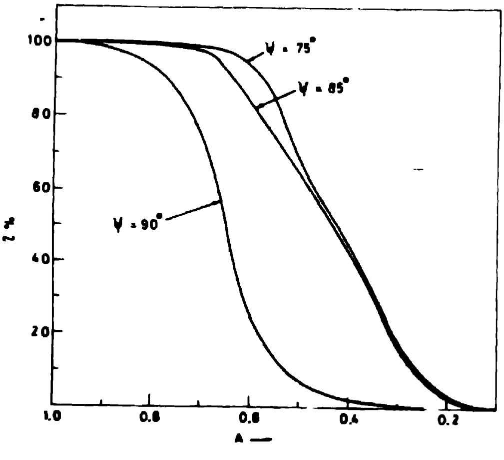

Figure 6. Variation of radiation efficiency with plasma parameter for different half cone angles

The variation of radiation efficiency of a conically depressed microstrip patch antenna is obtained and plotted for different half-cone angle ψ and plasma parameter (A) in Figure 6.

Bandwidth :

The total energy stored per cycle and hence Q factor of a conically depressed microstrip antenna are calculated using relations of [6]. For simplification, dielectric loss and copper loss are considered to be negligible. The bandwidth of present radiator is calculated theoretically for different values of plasma to source frequencies and are presented in Table 1.

Table 1. Bandwidth of a conically depressed microstrip radiator with different (A) and ψ values.

A	Bandwidth (%)		
	$\psi = 90°$	$\psi = 85°$	$\psi = 75°$
1.0	10 39	31.00	250.40
0.9	8 16	24.37	196 26
0.8	6 29	19.90	160.88
0.7	4 35	13.13	105.98
0 6	3 12	9 75	78.60
0.5	1 96	5.90	47 79
0.4	1.17	3 25	26 60
0.3	0 94	1 82	14.60
0.2	1 05	1.90	15.20
0.1	1.42	2.13	17.10

For computation purpose, h = 0.158 cm, ε_r = 2.31, f_r = 2.7 GHz and a = 2.1 cm are used.

4. Results and discussion

The radiation patterns of a conically depressed microstrip patch antenna are greatly affected due to presence of a plasma medium. Figure 1 shows $|E_\theta|$ patterns of a radiator in free space (A = 1.0) and in a plasma medium (A = 0.5). It is clear from Table 2 that 3dB beamwidth in

Table 2. Half power beamwidth of a conically depressed microstrip radiator for A = 1.0 and A = 0.5.

ψ	$\lvert E_\theta \rvert$		$\lvert E_\phi \rvert$	
	A = 1.0	A = 0 5	A = 1 0	A = 0.5
90°	104°	180°	148°	136°
85°	54°	124°	112°	100°
75°	45°	60°	60°	84°

free space decreases as angle ψ decreases and radiations will get concentrated in a narrow region. Similar results can be observed for plasma medium. For $\psi = 90°$ (circular patch), radiations are almost omnidirectional but on reducing ψ value, 3dB beamwidth reduces significantly.

It may be pointed out here that the intensity of $|E_\theta|$ pattern is much less in an ionized medium than that in free space, for all ψ values. Similar trend can be observed for $|E_\phi|$ pattern as shown in Figure 2. The only difference between $|E_\theta|$ and $|E_\phi|$ pattern is that in $|E_\phi|$ pattern, plasma medium marginally effects radiation patterns while in $|E_\theta|$ pattern, effect of a plasma medium is quite significant. $|E_p|$ patterns show the presence of innumerable maxima and minima similar to a discrete ray like structure.

It is clear from Table 1 that in free space, bandwidth is maximum for the structure having $\psi = 75°$. However, in a plasma medium, bandwidth of all the three structures under consideration decreases considerably on increasing plasma to source frequency value.

When an antenna interacts with a plasma medium, in addition to usual electromagnetic waves, electroacoustic waves will also be generated. Presence of these electroacoustic waves are perhaps responsible for such a change in the radiation properties in a plasma medium.

Due to depression of patch inside the dielectric, the field under the patch bends as shown in Figure 1(b). These bended fields form approximately a spherical wavefront and the waves in the free space travel spherically. Hence mismatch decreases gradually and more radiations are expected practically. This situation is similar to that of a horn antenna

The variations of radiation conductance in the electromagnetic mode and plasma mode with plasma parameter are shown in Figure 5. The radiation conductance in the electromagnetic mode for different values of ψ decreases with decreasing the value of plasma parameter, whereas in a plasma mode, the radiation conductance increases on decreasing the value of a plasma parameter. Furthermore, the radiation conductance in the electromagnetic mode and in a plasma mode has higher values at $\psi = 75°$ for all plasma parameter (A) values.

The variation of efficiency of such an antenna with a plasma parameter (A) is shown in Figure 6. Efficiency of such a radiator decreases with decreasing plasma parameter values but the efficiency of a conically depressed microstrip antenna ($\psi = 75°$ and $85°$) is much higher than a circular patch antenna ($\psi = 90°$). On the other hand as the depression in the substrate increases (ψ decreases), efficiency of the radiator increases.

5. Conclusions

From the study of various parameters it can be concluded that the effect of a plasma medium on the radiation properties of a conically depressed microstrip antenna is quite significant and interesting. The magnitude of fields and directivity of the antenna decreases sharply in the presence of a plasma medium. Plasma fields are longitudinal in nature and do not contribute to radiation or reception of electromagnetic waves. Hence, energy radiated in plasma field, decreases the bandwidth and efficiency of such a radiating system even though it is much higher than the radiation efficiency of a circular patch antenna with same dimensions. Using a microwave measurement set-up, experimental observations at 9 GHz frequency with circular microstrip patch (ψ = 90°) are taken and presented in Figure 7.

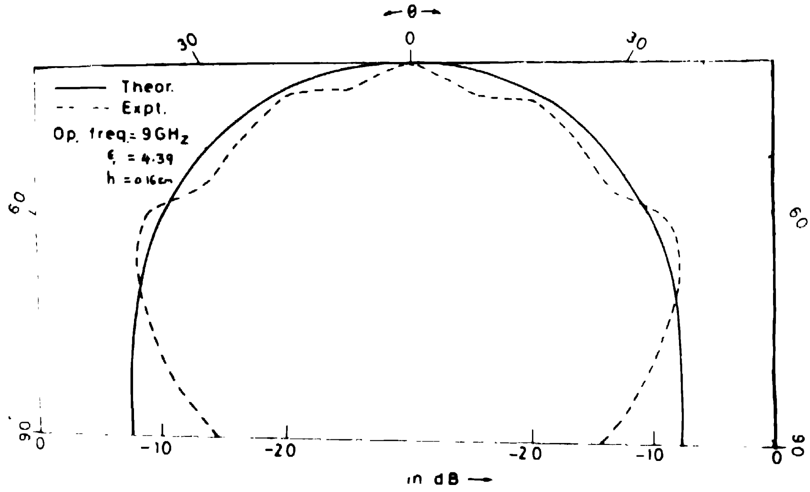

Figure 7. $|E_\theta|$ pattern of a radiator when ψ = 90° (circular patch) in free space

Measured relative dielectric constant (ε_r) and the dielectric loss tangent (tan δ) of a substrate are 4.39 and 0 01 respectively. On comparing theoretical $|E_\theta|$ pattern at 9 GHz with observed $|E_\theta|$ pattern in free space (with ψ = 90°), a good agreement can be found More observed and calculated parameters are given in Figure 7. Work on other geometries (ψ = 75° and 85°) is in progress and will be communicated later

An experimental verification of these results in free space as well as in a plasma medium at higher frequencies is required. An experimental verification similar to one performed by [7] for linear dipole antenna may be tried which may give additional information about the effect of a plasma medium on the radiation properties of such an antenna, though simulation of natural plasma medium in laboratory is a very difficult task.

Acknowledgment

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